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**Title:** Continuous cover forestry is a cost-efficient tool to increase multifunctionality of boreal production forests in Fennoscandia

**Year:** 2017

**Version:**

**Please cite the original version:**

Peura, M., Burgas Riera, D., Eyvindson, K., Repo, A., & Mönkkönen, M. (2017). Continuous cover forestry is a cost-efficient tool to increase multifunctionality of boreal production forests in Fennoscandia. *Biological Conservation*, 217, 104-112. <https://doi.org/10.1016/j.biocon.2017.10.018>

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1 **Title:** Continuous cover forestry is a cost-efficient tool to increase multifunctionality of boreal production  
2 forests in Fennoscandia

3

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17

18 **Abstract:**

19 Earlier research has suggested that the diversification of silvicultural strategies is a cost-efficient tool to  
20 ensure multifunctionality in production forests. This study compared the effects of continuous cover  
21 forestry and conventional rotation forestry on ecosystem services and biodiversity in boreal forests in  
22 Finland. We simulated over 25,000 commercial forest stands for 100 years under continuous cover and  
23 rotation forest management. Forests without management were used as a reference. We compared the  
24 effects of silvicultural practices over space and time on ecosystem services, biodiversity indicators and  
25 multifunctionality. Our results revealed that continuous cover forestry was better than rotation forest  
26 management in terms of timber net present value, carbon sequestration, bilberry production, scenic beauty  
27 and the number of large trees. It provided higher habitat availability for indicator species dependent on  
28 deciduous trees and mature forest structure. Rotation forest management was better than continuous cover  
29 forestry in terms of harvested tree biomass, cowberries, mushrooms, and species dependent on high tree  
30 volume. In general, multifunctionality was higher in continuous cover forests than in rotation forest.  
31 Therefore, continuous cover forests may have a greater potential to produce simultaneously multiple  
32 benefits from forests. However, unmanaged forests often provided the highest levels of services and  
33 biodiversity making their role indispensable in delivering forest related ecosystem services and,  
34 especially, in the maintenance of biodiversity. Continuous cover forestry does not itself guarantee the  
35 maintenance of all ecosystem services and biodiversity in commercial forests but it can be an important  
36 part of a successful progression towards more sustainable forestry.

37

38 **Key words:** biodiversity, ecosystem service, even-age, set aside, sustainability, uneven-age

39 **1. INTRODUCTION**

40 Forests are crucial in delivering ecosystem services for human wellbeing. During the last decades many  
41 forests in the boreal zone have been managed for intensive timber production applying conventional even-  
42 aged rotation forest management (hereafter RFM) while largely disregarding management effects on  
43 biodiversity and other forest ecosystem services (Burton et al., 2010; Gauthier et al., 2015; Vanhanen et  
44 al., 2012). Solely focusing on timber production, RFM has resulted in a biodiversity decline in production  
45 forests (Bradshaw et al., 2009; Siitonen, 2001; Östlund et al., 1997). Moreover, RFM can disturb nutrient  
46 cycling, increase land erosion and decrease water quality (Laudon et al., 2011). The role of boreal forests  
47 in climate regulation is well known as they contain about one third of the global terrestrial carbon stock  
48 (Bradshaw and Warkentin, 2015; Pan et al., 2011). However, the common practice of RFM focusing  
49 solely on timber production reduces carbon storage in boreal forests compared with optimal forest  
50 management (Triviño et al., 2016). Focusing on timber production can also be in conflict with other  
51 economically beneficial forest uses, such as recreation and harvest of non-timber forest products (e.g.,  
52 berries and mushrooms) (Peura et al., 2016). Earlier research has shown that diversifying forest  
53 management is a cost-efficient tool for enhancing ecosystem services (Miina et al., 2016; Triviño et al.,  
54 2015) and biodiversity (Mönkkönen et al., 2014) in production forest landscapes. In addition, previous  
55 studies indicate that alternative silvicultural practices are needed to ensure the delivery of multiple  
56 benefits of forests (Puettmann et al. 2015, Felton et al. 2016).

57 Continuous cover forestry (henceforth CCF) has a long history throughout the world, however  
58 has been widely replaced by RFM for decades (O'Hara, 2002; Kuuluvainen et al., 2012; Pommerening  
59 and Murphy, 2004). Recently, CCF is returning as an important silvicultural alternative to RFM (Diaci et  
60 al., 2011). In CCF, single trees, or small group of trees, are removed from the forest usually every 15-20  
61 years (Pommerening & Murphy 2004; Laiho, Lähde & Pukkala 2011; Kuuluvainen, Tahvonen & Aakala  
62 2012). Trees regenerate naturally, and the structure of forests is often uneven-aged. Such forest  
63 management practice has been called 'near natural forestry' since it may mimic a natural forest state and  
64 natural disturbances better than RFM (Kuuluvainen et al., 2012).

65 Previous research in boreal forests has shown that CCF is better than RFM from the perspective  
66 of berry production, the amenity of forest landscape, carbon balances and resistance against wind  
67 (Pukkala, 2016a; Pukkala et al., 2016, 2011). Moreover, CCF may be economically more profitable than  
68 rotation forest management for forest owners (Pukkala, 2016a; Tahvonen, 2016; Tahvonen et al., 2010;  
69 Tahvonen and Rämö, 2016). However, there are also contradictory results, regarding the economic  
70 profitability (Andreassen and Øyen, 2002) as well as the effects on climate regulation (Lundmark et al.  
71 2016) and resistance against disturbances (Hanewinkel et al., 2014). Consequently, the debate on the  
72 usefulness of CCF is still ongoing (Diaci et al., 2011). Even though CCF may often outperform RFM at  
73 the stand level, we do not know the relative performance of these management practices at a large  
74 landscape scale nor do we know the potential benefits a combination of these practices may have for  
75 ecosystem services and biodiversity across the landscape.

76 In general, CCF may provide more habitats and resources for species living in mature or late  
77 successional forests compared with RFM (Calladine et al., 2015; Kuuluvainen et al., 2012; Pukkala et al.,  
78 2012). In boreal forests, CCF has been found to be less harmful than RFM, for example, for understorey  
79 vegetation (Jalonen and Vanha-Majamaa, 2001), some invertebrate species (Matveinen-Huju and  
80 Koivula, 2008), and soil fauna (Siira-Pietikäinen and Haimi, 2009). Moreover, in comparison to RFM,  
81 CCF may provide more resources for dead wood dependent species (Atlegrim and Sjöberg, 2004) as well  
82 as for herbivores (Atlegrim and Sjöberg, 1996). However, because different species require differing  
83 habitats and resources, it is obvious that no single management can be the best for all species and  
84 biodiversity aspects (Calladine et al., 2015; Mönkkönen et al., 2014). Thus, it is important to understand  
85 how the different silvicultural practices promote different types of forest structures and species (Felton et  
86 al., 2016).

87 Even though there is evidence that CCF is better than RFM for several forest purposes (Pukkala,  
88 2016a), their relative performance of ecosystem service provisions and of biodiversity is not well known  
89 when compared with unmanaged forests (but see Pukkala, 2016b; Sharma et al., 2016). Even if there is a  
90 seemingly large difference between the two silvicultural alternatives, they may both appear equally poor

91 relative to forests in a more natural state. If so, then CCF may not be the solution to declining biodiversity  
92 and ecosystem services. Therefore, comparing both practices with unmanaged forests generates valuable  
93 knowledge about their actual effects on the ability of forest landscapes to provide goods and benefits to  
94 humankind.

95 As forests provide multiple services and benefits, the capabilities of alternative forest  
96 management practices should be assessed from a multifunctionality perspective, i.e., their relative  
97 performance to provide bundles of services simultaneously (Mastrangelo et al., 2014; van der Plas et al.,  
98 2016). Although earlier results demonstrate the high potential of CCF to simultaneously provide multiple  
99 services (Pukkala, 2016a), the concept of multifunctionality has not been commonly applied.  
100 Multifunctionality of forests can be considered as an index, which highlights the number of services  
101 which exceed a specified level of those services (van der Plas et al., 2016). Therefore, when estimating  
102 the capacity of different silvicultural practices to provide multiple benefits simultaneously, the effect of  
103 desired level of services should be taken into account.

104 We use a dataset describing a large forest landscape where we apply three alternative  
105 management practices —CCF, RFM and set aside (no management)— simulated for 100 years into the  
106 future to estimate their relative performance to provide forest ecosystem services and maintain  
107 biodiversity. We address the following questions: 1) Which ecosystem services and biodiversity measures  
108 benefit more from CCF compared with RFM and vice versa? 2) What are the levels of biodiversity and  
109 ecosystem services under two alternative forest management practices as well as their optimal  
110 combination compared with unmanaged forests? 3) Which silvicultural practice provides the greatest  
111 forest multifunctionality across large forest landscapes?

112

## 113 **2. METHODS**

### 114 **2.1 Forest data and simulations**

115 The study areas are located in central and southern Finland, encompassing 39,979 hectares. Data consist  
116 of 26,024 commercial forest stands on mineral soils with the average size of stands being 1.5 ha. The

117 initial forest data was provided by the Finnish Forest Centre, and are based on laser scanned data with  
118 ground-truthing (Maltamo et al., 2007). The data contain forest characteristics, such as forest site type,  
119 age, or tree species compositions. In the initial data, Scots pine (*Pinus sylvestris*) was the dominant tree  
120 species on 23% of the stands, Norway spruce (*Picea abies*) on 63% of the stands and birches (*Betula*  
121 *pendula* and *B. pubescens*) on 14% of the stands. Mixed stands, i.e., where none of the tree species  
122 accounted for more than 75% of the total volume, represent 45% of all the stands. The variation in the  
123 site type and initial age of stands are given in Appendix S1: Figure S1.

124 The development of each stand was simulated 100 years into the future using SIMO-forest  
125 simulator (Rasinmäki et al., 2009) under three different forest management regimes: CCF, RFM, and no  
126 silvicultural management (set aside, SA). We chose a time scale of 100 years since it is long enough to  
127 cover an entire rotation, and thereby to reveal the long-term impacts of silvicultural practices. The forest  
128 simulations create forest structural data at 5 year intervals.

129 In CCF, a selection of the largest trees is removed from the forests approximately every 15 years.  
130 Through natural regeneration, the composition of tree species becomes more mixed (Appendix S1; Figure  
131 S2). Over time, CCF changes the forest age structure to uneven-aged containing different age classes of  
132 trees. No retention trees were left (trees retained permanently through 100 years). The management rules  
133 for cuttings are given in Appendix S1: Table S1 (according to the good practice guidance for forestry in  
134 Finland from Äijälä et al., 2014). For CCF regime, the growth models of Hynynen et al. (2002) were used  
135 until the first cutting and then the growth models of Pukkala et al. (2013) for uneven-aged forests were  
136 used (Appendix S1: Figure S3). The model set of Hynynen et al. (2002) consists of species-specific  
137 individual-tree models for ingrowth, growth and mortality. The model set of Pukkala et al. (2013)  
138 consists of species-specific individual-tree diameter increment and survival models, and a stand level  
139 model for ingrowth.

140 RFM is currently the recommended and the most common forest management practice in  
141 Fennoscandia (Äijälä et al., 2014). In Finland RFM includes several silvicultural actions: soil preparation,  
142 seeding or planting trees, one to three thinnings, and the final clear cut, where approximately five

143 retention trees per hectare are retained (according to the good practice guidance for forestry from Äijälä et  
144 al., 2014). The management rules for regeneration cutting are given in Appendix S1: Table S2. The  
145 average rotation length of RFM is approximately 80 years in our study region (Appendix S1; Figure S2).  
146 RFM creates forest stands, which are often very homogenous in tree species composition as well as in the  
147 age structure. The growth models of Hynynen et al. (2002) for even-aged stands were applied for this  
148 regime.

149 In SA regime, forests are allowed to grow without human intervention (Appendix S1; Figure S2).  
150 In SA, forests are denser, grow slower and there is more tree competition compared with managed forests  
151 resulting in higher self-thinning and tree mortality. The models of Hynynen et al. (2002) were applied to  
152 simulate forest growth without management actions since they predict better the development of old-  
153 growth forests than the models of Pukkala et al. (2013).

154

## 155 **2.2 Ecosystem services and biodiversity indicators**

### 156 **2.2.1. Ecosystem services**

157 Different ecosystem categories (provisioning, regulating, and cultural) were considered with a set of  
158 ecosystem services (Table 1). Timber production is the economically most important provisioning service  
159 in boreal forests (Vanhanen et al., 2012). The net present value (NPV, €) of sawlogs and pulpwood for  
160 each tree species across 100 years was estimated. *The timber NPV* consists of three components: the  
161 revenues from harvesting (clear-cuts, thinnings, selective loggings; Appendix S1: Table S3), the value of  
162 standing timber at the end of simulations, and the value of spare land at the end of simulations (Pukkala,  
163 2005). In addition, timber NPV accounted for costs resulting from silvicultural actions related to  
164 regeneration and young stand (Appendix S1: Table S4). The stumpage prices of harvest revenue  
165 components and the prices for the silvicultural costs were calculated from the historical averages in  
166 Finland (Peltola 2014, Appendix S1: Table S3). The stumpage prices included costs from harvesting. The  
167 harvesting costs are higher in partial cuttings in CCF than in final fellings in RFM (e.g., Pukkala, 2016,  
168 Tahvonen et al., 2010) so the prices from second thinnings (also called intermediate felling) were used for



169 CCF. The interest rate varied between 1% and 5% in discounting the timber revenues and costs during the  
170 100-year period. In addition, to study the sensitivity of timber NPV with different costs and prices in CCF  
171 and RFM, we calculated NPV without regeneration costs in RFM and using the same prices for CCF and  
172 RFM. Timber revenues can be seen as a service for private forest owners, and thus, we also estimated the  
173 amount of harvested timber biomass separately for pulpwood and sawlogs, which can be considered as a  
174 provisioning service for the whole society since the forest industry is dependent on biomass.

175 Carbon storage and sequestration are important climate regulating services (Pan et al., 2011).  
176 Carbon storage was calculated as the amount of carbon in tree biomass and in soil. Total tree biomass  
177 (aboveground and belowground biomass) was estimated within the forest simulator and the amount of  
178 carbon in biomass was calculated by multiplying the total tree biomass by 0.5. Carbon in litter and soil  
179 was modelled using Yasso07 model (Liski et al., 2005; Tuomi et al., 2011, 2009). Carbon sequestration  
180 was calculated based on differences in the total carbon storage between consecutive time steps.

181 Non-timber forest products are economically valuable provisioning services as well as  
182 recreationally valuable cultural services in boreal forests (Vaara et al., 2013). The yields of two most  
183 common berries, bilberry (*Vaccinium myrtillus*) and cowberry (*V. vitis-idaea*), were estimated using  
184 models of Miina et al. (2009) and Turtiainen et al. (2013) following the methods of Miina et al. (2016).  
185 The marketed mushroom yields for spruce dominated stands were calculated using the model of  
186 Tahvanainen *et al.* (2016). In addition, scenic beauty of forests was estimated to describe their  
187 recreational values. The scenic beauty index was calculated based on forest age, density and tree species  
188 composition according to Pukkala et al. (1988) (Table 1).

189

### 190 **2.2.2. Biodiversity**

191 Biodiversity is a multi-faceted phenomenon, which can be measured using indices derived from forest  
192 structural data (Table 1). Dead wood is a critical resource in boreal forests (Siitonen, 2001). In boreal  
193 Fennoscandia, 20-25% of the forest-dwelling species are dependent on dead-wood habitats, and species  
194 dependent on dead wood constitute 60% of the red-listed species (Rassi et al., 2010). Association between

195 dead-wood volume and biodiversity is well established (Gao et al., 2015). The capacity of a stand to  
196 maintain populations of dead-wood associated species was estimated by multiplying total dead-wood  
197 volume by the diversity of deadwood across tree species, diameter and decay stage categories (Triviño et  
198 al., 2016). Thus, a stand with large total deadwood volume distributed evenly across deadwood types will  
199 receive high values of deadwood availability. In addition, large diameter living trees are an essential  
200 structural feature in boreal forests that has become a limiting factor for biodiversity in production forests  
201 (Nilsson et al., 2002). Therefore, the number of large diameter (>40 cm) trees was also calculated.

202 Habitat availability for species measure the overall capacity of the forests to maintain species  
203 populations. Habitat suitability indices (HSI) were calculated for a selected set of umbrella or indicator  
204 species representing habitat associations as well as social and conservation values: Capercaillie (*Tetrao*  
205 *urogallus*), Hazel grouse (*Bonasa bonasa*), Lesser spotted woodpecker (*Dryobates minor*), Long-tailed tit  
206 (*Aegithalos caudatus*), Three-toed woodpecker (*Picoides tridactylus*), and Siberian flying squirrel  
207 (*Pteromys volans*) (Table 1, Mönkkönen et al. 2014). Earlier research has shown that these species  
208 indicate forest characteristics important for many other species (please see Mönkkönen et al. 2014 for the  
209 detailed motivation to focus on these taxa). Our main focus is on late successional species due to their  
210 severe conservation need in Fennoscandia (Rassi et al., 2010). Habitat suitability is a function of a set of  
211 sub-utility functions based on expert knowledge and known species habitat that translate characteristics of  
212 each stand into a habitat suitability index between 0 (unsuitable habitat) and 1 (the most suitable habitat).  
213 For each species, we calculated habitat availability across the entire landscape as a sum of products  
214 between stand specific HSI-values and the area of a stand.

215

### 216 **2.2.3 Comparison between silvicultural practices**

217 To estimate the performance of silvicultural practices in maintaining ecosystem services and biodiversity  
218 (Table 1), their levels under CCF and RFM at a landscape scale across 100 years were calculated.  
219 Moreover, the share of stands when CCF outperforms RFM and vice versa was calculated. To estimate  
220 the maximum achievable levels of ecosystem services and biodiversity under the combination of CCF and

221 RFM, the practice that provided a larger value was applied for each stand. To estimate the relative  
222 performance of silvicultural strategies compared with unmanaged forests in the delivery of ecosystem  
223 services and biodiversity, their values under CCF, RFM, and their optimal combination (CCF+RFM)  
224 were divided by the values in SA forests. In the cases of timber net present value and harvested timber  
225 biomass, the optimal values (CCF+RFM) were used as a reference state since the value of SA regime was  
226 zero.

227 Especially in the cases of habitat and ecological resources, their uninterrupted availability is  
228 important for species persistence (Hanski, 1999; Ranius et al., 2008). Therefore, to estimate the temporal  
229 continuity of habitats at a stand scale, we calculated the number of cases across stands and time steps  
230 under each management practice when the habitat availability index was zero, i.e., when a stand is totally  
231 unsuitable for a given species.

232

#### 233 **2.2.4 Multifunctionality**

234 To estimate the potential of different silvicultural strategies to provide different services and biodiversity  
235 simultaneously the forest multifunctionality was estimated. The forest stand multifunctionality value was  
236 calculated using the formula from the study of van der Plas et al. (2016) as

$$237 \quad SMF_i = \frac{obsSMF_i - minSMF_i}{maxSMF_i - minSMF_i}$$

238 where  $SMF_i$  indicates a scaled multifunctionality value (between 0 and 1) of a single ecosystem service or  
239 biodiversity measure  $i$  in a stand over 100 years (Table 1),  $obsSMF$  indicates the observed value of a  
240 single biodiversity or ecosystem service measure in a stand,  $minSMF$  and  $maxSMF$  indicate the minimum  
241 and the maximum values of a single biodiversity or ecosystem service measure in the whole study area.

242 The ecosystem services and biodiversity measures were divided into four groups according to the  
243 ecosystem service categories they represent (Haines-Young and Potschin, 2011): provisioning services  
244 (timber NPV and harvested timber biomass), regulating services (carbon storage and sequestration), and  
245 cultural services (scenic beauty and the combined yield of bilberries and cowberries). In addition, a

246 category representing biodiversity consisted of dead wood diversity and combined habitat suitability  
247 index—a combination of six habitat suitability indices (Triviño et al., 2016). Grouped SMF (GMF) takes  
248 value 1 if either of the SMF in a group was larger than the threshold value  $t$ . Finally, multifunctionality  
249 score of a stand was calculated as the sum GMFs that had a value above a threshold  $t$  as follows:

$$250 \quad MF = \sum_{i=1}^n \begin{cases} 1 & GMF_i \geq t \\ 0 & GMF_i < t \end{cases}$$

251 where  $GMF_i$  indicates a scaled multifunctionality value (between 0 and 1) of a grouped ecosystem  
252 (provisioning, regulating and cultural) or biodiversity measure  $i$  in a stand where threshold  $t$  was  
253 continuous between 0 and 1. The maximum multifunctionality score is 4 when a stand is able to provide  
254 all services and biodiversity above the threshold level, and minimum is 0 indicating that all indicators  
255 remain below the threshold. We calculated average multifunctionality score over time and space in the  
256 data. The threshold was varied between 0 and 1 to see if the relative utility of alternative management  
257 regimes from multifunctionality perspective changes with the desired level of functionality. High  
258 threshold values denote situations where the society aspires for high levels of all ecosystem services and  
259 biodiversity, while low value refers to a low societal need for multifunctionality.

260

### 261 **3. RESULTS**

#### 262 **3.1. Ecosystem services**

263 CCF provided higher values than RFM for five out of eight ecosystem services at the landscape scale on  
264 average over 100 years (Figure 1a,2a; Appendix S2: Table S1,S2). Carbon storage was moderately higher  
265 and sequestration remarkably higher in landscapes consistently managed using CCF in comparison with  
266 RFM (Figure 1a; Appendix S2: Figure S1). In terms of the regulating services, CCF outperformed RFM  
267 in approximately 75% of the stands (Figure 1b). Bilberry yields and scenic beauty were higher with CCF  
268 (Figure 1a) and CCF outperformed RFM in 70–90% of the stands (Figure 1b). In contrast, cowberry and  
269 marketed mushroom yields were higher in RFM (Figure 1a) and it outperformed CCF in approximately  
270 90% of the stands (Figure 1b).

271 RFM provided more harvested timber (Figure 2a; Appendix S2: Table S1) outperforming CCF in  
272 60% of the stands (Figure 2b). There were differences in the shares of sawlogs and pulpwood between  
273 CCF and RFM (Appendix S2: Figure S2). In CCF, 79% of the harvested timber was sawlogs and 21%  
274 pulpwood, whereas in RFM the share of sawlogs was 65% and the share of pulpwood 35%.

275 The discount rate affected the economic performance of CCF and RFM (Figure 2a; Appendix S2:  
276 Table S2). With a 1% discount rate, the NPV of both strategies was the same. The timber NPV was  
277 greater in CCF than in RFM when the discount rate was 2% or larger. The optimal share of CCF and  
278 RFM was 50% of each when the discount rate was 1% (Figure 2b). The optimal share of CCF increased  
279 with the discount rate and was 80% at 5% discount rate. Only when the costs related to regeneration and  
280 young stands were not taken into account and the discount rate was 1%, the NPV was greater in RFM  
281 than in CCF (Appendix S2, Figure S3c).

282 The optimal combination of CCF and RFM provided higher levels of ecosystem services than  
283 either of them separately in all cases except in cowberry yields (Figure 1a, 2a). The benefit of applying  
284 both regimes in landscapes was the largest for harvested timber and timber NPV (Figure 2a).

285 SA forests provided higher values than CCF, RFM or their combination particularly for the climate  
286 regulating services but also for scenic beauty (Figure 1). Managed forests tended to provide a higher  
287 delivery of collectable goods than SA forests. However, SA performed as well as CCF in marketed  
288 mushroom production and as well as RFM in bilberry production.

289

### 290 **3.2 Biodiversity**

291 Consistent application of CCF in landscapes yielded higher values than RFM for five out of eight  
292 biodiversity indicators (Figure 3a; Appendix S2: Table S3). For three biodiversity indicators (Lesser  
293 spotted woodpecker, Long-tailed tit and number of large diameter trees) CCF outperformed RFM in  
294 almost 100% of stands (Figure 3b) and the difference in favour of CCF was remarkably large (Figure 3a).  
295 CCF also yielded clearly higher values than RFM in the cases of Hazel grouse and Three-toed  
296 woodpecker when CCF outperformed RFM in between 70% to 80% of the stands. In contrast, RFM

297 yielded slightly higher dead wood indicator values outperforming CCF in 67% of the stands. Moreover,  
298 for the Capercaillie and flying squirrel consistent application of RFM clearly performed better than CCF  
299 (Figure 3a) providing higher habitat suitability index in between 50% to 97% of the stands (Figure 3b).

300 In five cases, a combination of CCF and RFM provided higher scores than either of them separately  
301 (Figure 3a). The benefits of combining the two management practices in landscapes were particularly  
302 pronounced for the Capercaillie and the Hazel grouse. For the Capercaillie, the combination of CCF and  
303 RFM (Figure 3b) yielded 55% larger HSI value than consistent application of CCF and 30% larger than  
304 consistent application of RFM (Figure 3a). For the Hazel grouse, the combination (Figure 3b) yielded  
305 65% larger HSI value than consistent application of RFM and 20% larger than consistent application of  
306 CCF (Figure 3a).

307 From biodiversity perspective, SA was always clearly better than RFM (Figure 3a). For two  
308 biodiversity indicators (habitat availability for the Hazel grouse and the Lesser-spotted woodpecker), CCF  
309 and SA performed equally well, while in two cases CCF outperformed SA: CCF provided ten times  
310 higher number of large trees, and more than two times higher habitat availability for Long-tailed tit than  
311 SA (Appendix S2: Table S3).

312 The frequency of unsuitable habitats varied among species (Figure 4). For the Capercaillie,  
313 practically all stands were unsuitable at some point of time irrespective of the management regime. For  
314 other species except the Siberian flying squirrel, the frequency of total unsuitability was the highest under  
315 RFM. SA showed the lowest frequency of total unsuitability for all other species except the Long-tailed  
316 tit when CCF performed the best.

317

### 318 **3.3. Multifunctionality**

319 At all threshold levels, the average forest multifunctionality was larger when forests were managed with  
320 CCF than forests managed with RFM (Figure 5) indicating a larger capacity of CCF to simultaneously  
321 provide services from different categories. An optimal combination of CCF and RFM always produced  
322 higher multifunctionality scores than RFM alone, and slightly higher scores than CCF alone when the

323 threshold was larger than 0.4. This indicates that even though CCF in general is better from the  
324 multifunctionality point of view, there are some stands where RFM has higher potential to provide  
325 multifunctionality. SA provided the lowest multifunctionality below 0.4 threshold levels, which is  
326 primarily due to the lack of timber harvesting. When the demand for multifunctionality is high (threshold  
327 >0.6) SA forests provided the highest multifunctionality scores. This means that when high levels of  
328 ecosystem services and biodiversity are simultaneously desired, leaving forests unmanaged (set aside) is  
329 more desirable than managing forests (both CCF and RFM).

330

#### 331 **4. DISCUSSION**

332 Our results show that CCF has the potential to deliver ecosystem services and maintain biodiversity in  
333 commercial forests better than conventional RFM. In general, the results of this study are in line with  
334 previous research (Pukkala, 2016a; Shanin et al., 2016; Sharma et al., 2016). However, CCF was not  
335 better than RFM in terms of all ecosystem services or biodiversity indicators. Moreover, the optimal  
336 combination of CCF and RFM provided higher values of ecosystem services and biodiversity measures  
337 than either CCF or RFM applied consistently in all stands. Previous studies have also shown the benefit  
338 of using a diverse set of silvicultural practices in forest landscapes (Mönkkönen et al., 2014; Redon et al.,  
339 2014; Triviño et al., 2016, 2015). Thus, the relative utility of silvicultural practice depends on site  
340 characteristics; an aspect that should be further studied.

341 In terms of regulating services, while there were no large differences between CCF and RFM in  
342 carbon storage, CCF outperformed RFM in carbon sequestration. In RFM, a stand is periodically a source  
343 of carbon after the clear-cut. This is mainly because the decomposing forest harvest residues release  
344 carbon more than is sequestered in the biomass growth. In CCF, changes in soil carbon stock are smaller  
345 after harvests than in RFM because the litter input from harvest residues is smaller. The carbon balance of  
346 forests critically depends on the final use of timber biomass after it is removed from the forest ecosystem  
347 (Lundmark et al., 2016; Pukkala, 2016b) but we did not take into account the carbon storage in wood  
348 products or emissions from the procurement chain. However, as the proportion of sawlogs compared with

349 pulpwood is higher in CCF than in RFM, the carbon retention time would be longer for timber produced  
350 in CCF (Pukkala, 2014). Therefore, inclusion of carbon storage in the wood products would not change  
351 the main findings. The superior capacity of unmanaged forests to sequester carbon is explained by the  
352 initial state of the forest stands and their management history. Intensively managed forest landscapes in  
353 Finland have a high proportion of young stands holding large potential for carbon sequestration. Although  
354 in SA the rate of carbon sequestration decreases with the increasing age of the forest (Pukkala, 2016b),  
355 we show that unmanaged forests can have a remarkable role in climate change mitigation for several  
356 decades.

357         Our results considering timber NPV support earlier findings (Pukkala et al., 2011; Tahvonen et  
358 al., 2010) where discount rates larger than 1% make CCF more profitable than RFM. Higher profitability  
359 of CCF is related to the higher price of sawlogs versus pulpwood (CCF provides more sawlogs) as well as  
360 the large costs of regeneration and thinnings in RFM. However, in some cases RFM provided also larger  
361 economic profits than CCF. This is the case, for stands that are mature, i.e. ready for final harvesting at  
362 the beginning of 100 year time period (Tahvonen et al., 2010). CCF is not commonly applied in  
363 Fennoscandia because of the uncertainty in regeneration success, lower timber quality and higher total  
364 harvesting costs (Laiho, Lähde & Pukkala 2011). The potential for lower timber quality and higher  
365 harvesting costs were accounted for by applying a lower price for timber originating from CCF. In  
366 addition, we estimated the NPV with and without taking regeneration costs into account for RFM. In  
367 contrast to NPV, RFM produced more harvested timber biomass, which is also supported by earlier  
368 studies (Lundqvist et al., 2007; Pukkala et al., 2011; Tahvonen et al., 2010). Thus, CCF may be more  
369 profitable for private forest owners while RFM may better meet the industry's current needs.

370         For four out of the six umbrella and indicator species, CCF provided higher habitat availability  
371 than RFM. This is not surprising since many species in this study are dependent on tree cover and  
372 deciduous trees, which CCF provides. Moreover, the frequency where the stands were totally unsuitable  
373 for the species was often highest in RFM. Thus, one benefit of CCF for mature forest species is the less  
374 severe temporal fluctuations in habitat quality. However, for early successional species RFM may



375 actually provide more habitats (Calladine et al., 2015). Nevertheless, habitat availability for species  
376 dependent on high tree volume and dead wood availability in forests under both CCF and RFM were far  
377 from those in unmanaged forests. Thus, some species habitat availability and dead wood availability more  
378 critically depend on the amount of harvested timber than on the silvicultural practice used in harvesting  
379 (Atlegrim and Sjöberg, 2004). For many deadwood dependent species, the desirable minimum level of  
380 dead wood is approximately  $20 \text{ m}^3 \text{ ha}^{-1}$  (Junninen and Komonen, 2011) while both CCF and RFM  
381 provided only about 25% of that. To further improve the ability of CCF to promote biodiversity we  
382 recommend a similar kind of green tree retention that is applied in RFM (leaving permanently behind, at  
383 least, 5 trees per ha) to be included in the CCF management regime. Interestingly, CCF provided the  
384 greatest number of large trees resulting from the larger resource availability of individual trees (space and  
385 light). In contrast, for unmanaged forests, tree growth is lower. This is likely due to the development and  
386 transition of very young and planted stands at the beginning of the simulation. For these stands, transition  
387 to uneven aged stands will take longer than 100 years and the large trees will likely be harvested during  
388 the next (or following) CCF cutting. However, if the simulation time had been longer than 100 years, the  
389 number of large diameter trees would have been larger in SA regime and on the other hand smaller in  
390 CCF since the transition from even-aged to uneven-aged forestry allows large diameter trees in our CCF  
391 simulations.

392 In general, our multifunctionality results indicate that CCF has greater potential than RFM to  
393 simultaneously produce multiple benefits in forests, which supports earlier findings (Pukkala 2016a;  
394 Sharma et al. 2016). With a moderate demand level for services (threshold value 40%), CCF  
395 simultaneously provided services from all categories when RFM provided services only from three  
396 categories. Moreover, the relative multi-functionality performance of SA increased with the demanded  
397 level of services. Therefore, when discussing the delivery of ecosystem services and maintaining  
398 biodiversity, their demanded levels should be taken into account. If society demands high  
399 multifunctionality in forest landscapes, more resources must be allocated to unmanaged set aside forests  
400 since their role in delivering high levels of biodiversity and regulating services is often indispensable.

401 In the simulation process, all management options were based on decision rules instead of  
402 optimizing the specific management at stand level. Both management alternatives that we used could be  
403 changed substantially by altering the specific decision rules (i.e. delaying final felling, restricting the  
404 frequency of harvests, or requiring green tree retention following a clear felling) to increase the delivery  
405 of multiple benefits in forest stands (e.g., Liski et al. 2001; Gustafsson et al. 2012). Optimizing the  
406 management at a stand level can improve the economic and ecological performance of a stand (e.g.,  
407 Miina, Pukkala & Kurttila 2016; Tahvonen & Rämö 2016). However, stand level optimizing is  
408 problematic for several reasons. First, there is high uncertainty, e.g., because of errors in inventory  
409 estimates and in inaccuracies in growth models resulting only in crude approximations. As a consequence,  
410 the actual performance of a stand level optimized management plan could fall short of the management  
411 plan following decision rules (Holopainen and Talvitie, 2006). Second, optimizing at the stand level is a  
412 time consuming and data intensive activity, and consequently not often practicable (Kurttila et al., 2013).  
413 Third, in practice management decisions depend on the choices of the forest owner, whose preferences  
414 may more likely be based on the personal economic situation rather than on specific stand characteristics  
415 (Brazeel, 2003). In such cases, simple decision rules may better provide guidance to decisions than  
416 knowledge about stand level optimal management.

417 Our comparison among CCF, RFM and unmanaged forests has some limitations. Even though the  
418 planning horizon was long (100 years), even set-aside forests do not provide a natural-state benchmark for  
419 managed forests. For example, the amount of dead wood in the natural forest state is approximately 60-90  
420  $\text{m}^3 \text{ha}^{-1}$  (Siitonen, 2001) but in our data the amount of dead wood under set-aside was significantly lower.  
421 Moreover, our simulation did not include natural disturbances, such as storms and diseases, which may  
422 substantially change the forest characteristics, e.g. dead wood volumes (Kuuluvainen, 2002). Therefore,  
423 our simulations probably underestimate the delivery of some ecosystem services and biodiversity values  
424 in all management regimes, and on the other hand, overestimate timber production in both CCF and RFM.  
425 Disturbances do occur in forests regardless of management but their intensity and effects vary depending  
426 on management of the stand itself and its surrounding forests. Since CCF maintains natural tree species

427 and more natural structure of forests it may be more resistant against the disturbances, such as wind  
428 damages (Couture et al., 2016; Pukkala et al., 2016), and insect pathogens (Klapwijk et al., 2016). We  
429 leave it as a challenge for future studies to accommodate disturbance effects on ecosystem services and  
430 biodiversity in forests under different management regimes. This would inevitably require a spatially  
431 explicit landscape level approach.

432 The role of unmanaged forests is central in delivering ecosystem services and maintaining  
433 biodiversity, and unmanaged forests should exist in commercial forested landscapes. One suggested way  
434 to protect biodiversity, habitats and ecosystems is the third-of-third approach (Hanski, 2011) where a third  
435 of the landscapes are managed as multi-use conservation landscapes within which a third of the land area  
436 is protected. Because CCF provides a cost-efficient option to manage forests for multiple purposes it  
437 could be applied in multi-use landscapes. Moreover, because CCF has the potential to maintain habitat  
438 connectivity (Pukkala et al., 2012) and may better provide corridors and stepping stones for species living  
439 in protected areas, it may well promote species persistence in managed landscapes if augmented with  
440 adequate levels of set-asides.

441

## 442 **5. CONCLUSION**

443 Our results indicate that continuous cover forestry has greater potential than rotation forest management  
444 to maintain multifunctional forests. However, continuous cover forestry was not the best for all ecosystem  
445 services or biodiversity indicators. Furthermore, the combination of different forest management practices  
446 provided higher levels of services and indicators than single practices applied consistently over the  
447 landscape. Moreover, we show that commercially managed forests, if set aside, may provide important  
448 resources for biodiversity and regulating services. Thus, it is not reasonable to rely on one single practice  
449 and careful landscape planning is needed. Continuous cover forestry does not itself guarantee the  
450 maintenance of all ecosystem services and biodiversity in commercial forests but it can be an important  
451 part of a successful progression towards more sustainable forestry.

452

453 **ACKNOWLEDGEMENTS**

454 We are grateful to Jenny and Antti Wihuri (to M.P.) and Kone foundations (project #46-10588 to M.M.)  
455 as well as the Academy of Finland (project #275329 to M.M.) for funding. We thank T. Heinonen for  
456 help in putting together the forest simulator.

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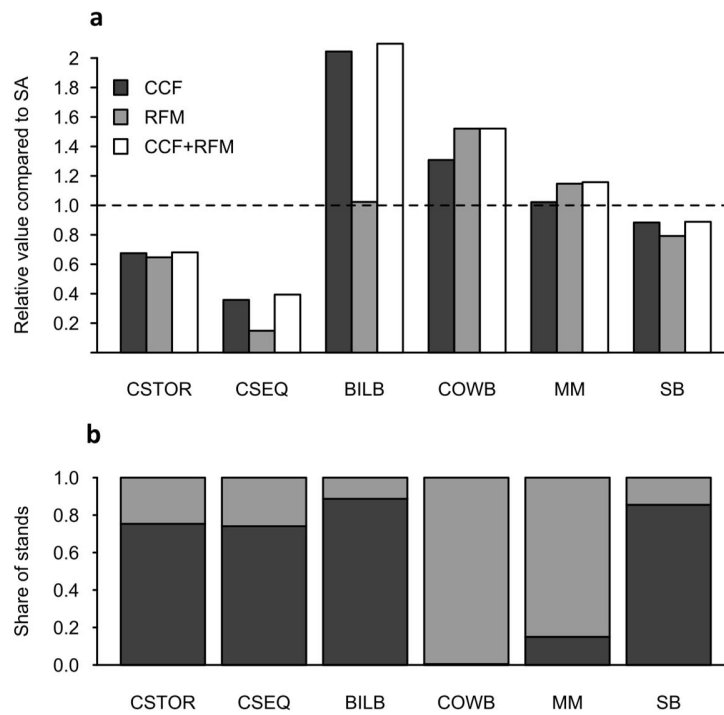
665 **Table 1** Ecosystem services and biodiversity indicators in the study.

	Abbreviation	Description
<b>Ecosystem services</b>		
Timber NPV	NPV	Timber net present value (€ha <sup>-1</sup> ) at different discount rates 1-5%
Harvested timber	HARV	Total harvested timber volume (m <sup>3</sup> ha <sup>-1</sup> , over 100 years)
Carbon storage	CSTOR	Carbon stored in the soil and in the biomass of living and dead trees (kgC ha <sup>-1</sup> , average over 100 years)
Carbon sequestration	CSEQ	Change in carbon storage between consecutive time steps (kgC ha <sup>-1</sup> year <sup>-1</sup> )
Bilberry	BIL	Bilberry yield (kg ha <sup>-1</sup> year <sup>-1</sup> )
Cowberry	COW	Cowberry yield (kg ha <sup>-1</sup> year <sup>-1</sup> )
Mushroom	MM	Marketed mushrooms yield (kg ha <sup>-1</sup> year <sup>-1</sup> )
Scenic beauty	SB	Scenic beauty of forest (ha <sup>-1</sup> , average over 100 years); increases with the size and age of trees, with a share of pines and deciduous trees, and with decreasing number of stems.
<b>Biodiversity</b>		
HSI Capercaillie	CC	Game bird with social and economic value, associated with pine volume (min 60 m <sup>3</sup> ha <sup>-1</sup> ) with intermediate spruce mixture and steam density (ha, average over 100 years)
HSI Hazel grouse	HG	Game bird species indicating adequate levels of deciduous mixture (20-40%) with spruce (>20%) (ha, average over 100 years)
HSI Lesser spotted wood pecker	LSWP	Indicator species associated with old deciduous trees (min 60 years) and deciduous snags (ha, average over 100 years)
HSI Three-toed woodpecker	TTWP	Indicator species associated with high volume of trees (min 60 m <sup>3</sup> ha <sup>-1</sup> ) and fresh deadwood (ha, average over 100 years)
HSI Long-tailed tit	LTT	Indicator species associated with mature forests (min 30 years) deciduous trees (20-60%) (ha, average over 100 years)
HSI Siberian flying squirrel	SFS	Red-listed species associated with high volume of spruce (min 140 m <sup>3</sup> ha <sup>-1</sup> ) with deciduous mixture (min 12 m <sup>3</sup> ha <sup>-1</sup> ) (ha, average over 100 years)
Dead wood	DW	Volume of dead wood weighted by diversity (m <sup>3</sup> ha <sup>-1</sup> , average over 100 years)
Large trees	N40	Number of trees with diameter > 40 cm (ha <sup>-1</sup> , average over 100 years)

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668 **FIGURES**



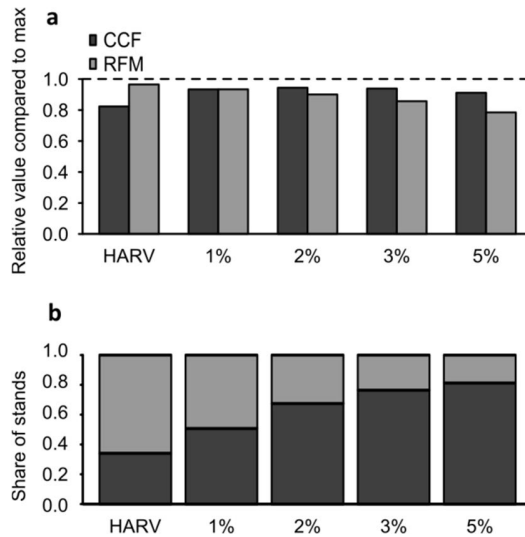
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670 **Figure 1** a) Relative ecosystem service values for carbon storage (CSTOR) and sequestration (CSEQ),  
 671 bilberry (BILB), cowberry (COWB), marketed mushrooms (MM), and scenic beauty (SB) under  
 672 continuous cover forestry (CCF), rotation forest management (RFM), and their optimal combination  
 673 (CCF+RFM) compared to set aside (1, the dashed line). Absolute values are given in Appendix S2: Table  
 674 S1. b) Optimal share of stands to maximize the provision of ecosystem service in the study area under  
 675 CCF and RFM.

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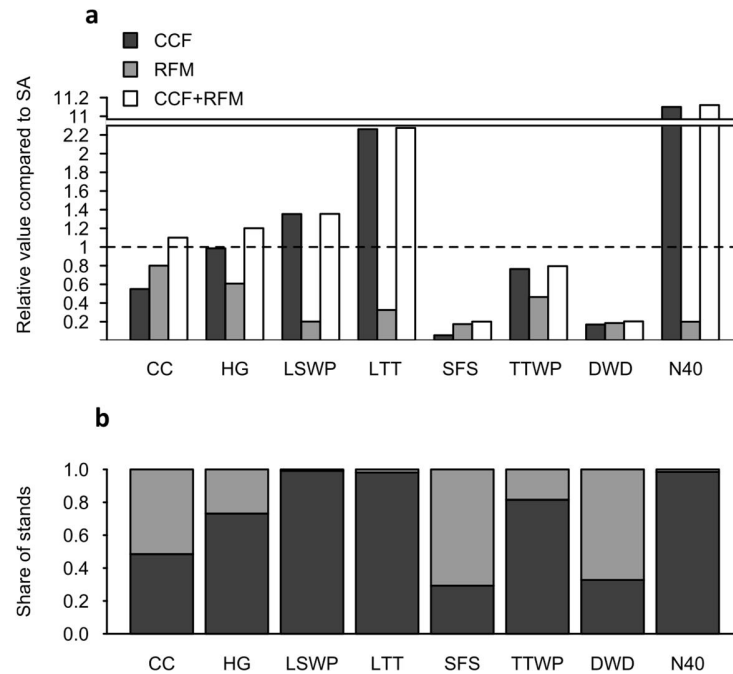
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680 **Figure 2** a) Relative harvested timber biomass (HARV) and revenues (NPV) with different discount rates  
681 (1-5%) in the study area under continuous cover forestry (CCF) and rotation forest management (RFM)  
682 compared to their optimal combination (CCF + RFM, the dashed line). Absolute values are given in  
683 Appendix S2: Table S1,S2. b) Optimal share of stands under CCF and RFM to maximize harvested  
684 timber and timber revenues in the study area.

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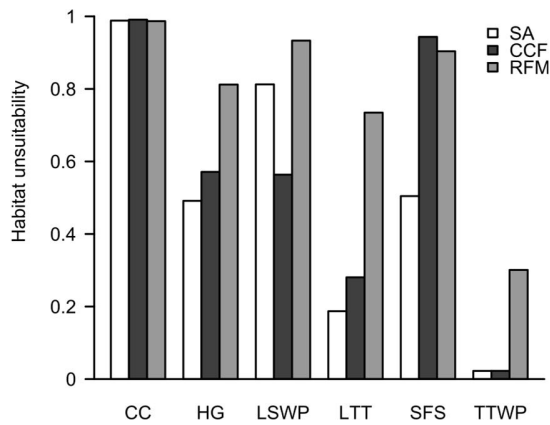
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690 **Figure 3** a) Relative biodiversity indicator values in the study area for Capercaillie (CC), Hazel grouse  
691 (HG), Lesser spotted woodpecker (LSWP), Long-tailed tit (LTT), Siberian flying squirrel (SFS), Three-  
692 toed woodpecker (TTWP), deadwood availability (DWD), and number of large diameter trees (N40)  
693 under continuous cover forestry (CCF), rotation forest management (RFM), and their optimal  
694 combination (CCF+RFM) compared to set aside (1, the dashed line). Please note that there is a break in  
695 the y-axis between values 2.2 and 11. Absolute values are given in Appendix S2: Table S3. b) Optimal  
696 share of stands under CCF and RFM to maximize timber revenues in the study area.

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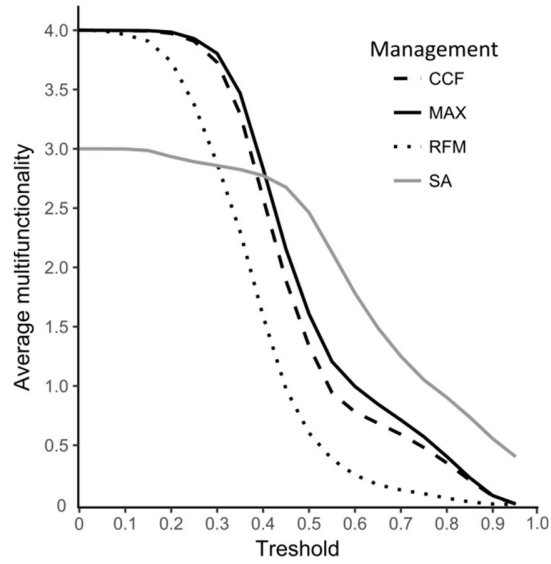
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699 **Figure 4** Relative frequency of cases when habitat suitability index was zero for the Capercaillie (CC),  
 700 Hazel grouse (HG), Lesser spotted woodpecker (LSWP), Long-tailed tit (LTT), Siberian flying squirrel  
 701 (SFS), and Three-toed woodpecker (TTWP), under set aside (SA), continuous cover forestry (CCF) and  
 702 rotation forest management (RFM).

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707 **Figure 5** Average forest multifunctionality values for 100 years in the study area under different  
708 threshold values for continuous cover forestry (CCF), rotation forest management (RFM), their optimal  
709 combination (MAX), and set aside (SA).

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